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THE NATURE OF THE COMPANION TO THE ECLIPSING OVERTONE CEPHEID MACHO 81.8997.87

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ABSTRACT

The lightcurve of the Large Magellanic Cloud (LMC) variable star MACHO 81.8997.87 shows evidence for photometric variations due to both stellar pulsation, with a 2.035 day period, and eclipsing behavior, with an 800.4 day period. The primary star of the system has been identified as a first-overtone Cepheid but the nature of the secondary star has not been determined. Here we present multicolor BVI photometry of a primary eclipse of the system and fit a model to the complete lightcurve to produce an updated set of elements. These results are combined with 2MASS JHK photometry to give further insight into the identity of the companion star. We find that the companion is most consistent with a late-K or an early-M giant but also that there are a number of problems with this interpretation. The prospects for future observations of this system are also discussed.

Subject headings: Magellanic Clouds — Cepheids — stars: oscillations — binaries: eclipsing

1. INTRODUCTION

There is a small but growing list of regularly pulsating stars that are known to be members of eclipsing binary systems. Alcock et al. (2002) present observations and analysis of three eclipsing Cepheid variables for which data exist in the MACHO Project Large Magellanic Cloud (LMC) database. Rodríguez & Breger (2001) list nine eclipsing binary systems that contain δ Scuti variables and new candidates have been identified since that time (see Dallaporta, Tomov, Zwitter, & Munari (2002) and Kim et al. (2003)). Most recently Soszynski et al. (2003) list three objects whose lightcurves show evidence for eclipses and RR Lyr-type pulsations. Although one or more of these may be the result of photometric contamination, clearly this is a burgeoning field for obtaining long-sought direct measurements of pulsating star properties.

The astrophysical returns from systems that combine eclipsing and pulsating behavior can be considerable. An eclipsing Cepheid system, if also a double-lined spectroscopic binary, can give a determination of the mass and luminosity of the Cepheid that is not only more accurate than existing measurements but also independent of assumed distance estimates. Such a system would offer an independent calibration of the period-luminosity and period-luminosity-color relations and the most direct measurement of the Cepheid's mass.

Here we present additional observations and an updated analysis of the eclipsing Cepheid system MACHO 81.8997.87. In particular, we more strongly constrain the nature of the system's secondary star.

2. OBSERVATIONS

The analysis presented here incorporates observations from four sources. The majority of the observations are from the MACHO Project photometric database. The collection process has been described in detail elsewhere (Alcock et al. 1995) so we give only a brief description here. The MACHO observations were made with the refurbished 1.27m Great Melbourne Telescope at Mount Stromlo Observatory (MSO), near Canberra, ACT, Australia. It was equipped with a prime focus reimager-corrector with an integral dichroic beamsplitter which gave a 0.5 sq. deg field of view in two passbands simultaneously: a 450-590 nm MACHO V filter and a 590-780 nm MACHO R filter. These were each sampled with a 2×2 array of 2048×2048 Loral CCDs which were read out concurrently via two amplifiers per CCD in about 70 seconds. The image scale was 0.63 arcsec per pixel. Data reduction was performed automatically by Sodophot, a derivative of DoPhot (Schechter, Mateo & Saha 1993). MACHO photometry was then transformed into Cousins V and R bands for further interpretation (Alcock et al. 1999).

The eclipsing nature of 81.8997.87 was first reported by the Optical Gravitational Lensing Experiment (OGLE) project Udalski et al. (1999) as OGLE LMC-SC16 119952. OGLE observations were taken on the 1.3 m Warsaw telescope at Las Campanas Observatory, Chile, operated by the Carnegie Institute of Washington. Photometry is in the standard BVI bands with the majority of the observations in the I band. MACHO and OGLE data for this system were previously published in Alcock et al. (2002).

Follow-up observations of the April 2001 primary eclipse were obtained in BVI over 16 nights on the 1.9 m telescope at MSO. It was equipped with a 2048×4096 SITe detector with a pixel size of 15 μm^2. The chip was binned 5×5 pixels resulting in a final image scale of 0.45 arcsec per binned pixel. Photometry was reduced using

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TABLE 1
B photometry of April 2001 primary eclipse obtained with the 1.9 m telescope at MSO.

HJD	B (mags)	σ_B (mags)
2451998.957875	18.219	0.030
2451998.959796	18.298	0.013
2451998.967262	18.306	0.014
2451998.974738	18.198	0.024
2452000.911406	18.342	0.013
2452000.918872	18.338	0.013
2452000.926349	18.347	0.013
2452002.898562	18.379	0.016
2452002.906039	18.435	0.019
2452002.962833	18.360	0.020
2452003.898742	18.306	0.015
2452003.906219	18.363	0.016
2452003.913696	18.314	0.016
2452004.883170	18.528	0.018
2452004.890646	18.512	0.018
2452004.898112	18.601	0.018
2452005.884403	18.445	0.020
2452005.891869	18.400	0.018
2452005.899358	18.414	0.018
2452007.905100	18.598	0.020
2452007.912577	18.665	0.023
2452008.880999	18.773	0.020
2452008.888475	18.804	0.022
2452008.895952	18.823	0.021
2452011.891229	18.443	0.013
2452011.898694	18.458	0.016
2452012.896051	18.598	0.014
2452012.903528	18.591	0.014
2452012.911004	18.589	0.012
2452013.881219	18.228	0.012
2452013.889228	18.226	0.012
2452013.896705	18.241	0.013
2452014.878934	18.434	0.016
2452014.886411	18.440	0.012
2452014.923345	18.451	0.013
2452014.931516	18.438	0.012
2452014.938981	18.463	0.012
2452015.865342	18.060	0.014
2452015.873236	18.092	0.014
2452015.880713	18.095	0.013

the IRAF[1], DAOPHOT, ALLSTAR and ALLFRAME packages. On several nights images of an NGC 1866 standard field were also taken and these observations were used to calibrate the photometry to the NGC 1866 standards of Walker (1995). The observations are tabulated in Tables 1-3 and the V observations can be seen in Figure 1. The B band observations were not incorporated in the analysis presented here for two reasons:

1. The lack of B photometry outside eclipse provides no useful baseline for an analytical fit.
2. They provide very little insight into the nature of the companion star as its color is so red (see below) that its contribution to the B flux is negligible.

To complement the optical observations listed above, additional photometry was extracted from 2MASS, a

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

TABLE 2
V photometry of April 2001 primary eclipse obtained with the 1.9 m telescope at MSO.

HJD	V (mags)	σ_V (mags)
2451998.933593	17.208	0.037
2451998.935768	17.175	0.037
2451998.941289	17.168	0.036
2451998.947667	17.181	0.035
2452000.873177	17.192	0.038
2452000.874856	17.118	0.038
2452000.875909	17.234	0.038
2452000.877610	17.231	0.038
2452000.879288	17.221	0.036
2452000.883281	17.228	0.036
2452000.887286	17.227	0.036
2452001.083492	17.426	0.036
2452001.085402	17.414	0.037
2452002.882451	17.256	0.036
2452002.887138	17.246	0.036
2452002.891837	17.238	0.035
2452003.867689	17.224	0.039
2452003.870363	17.115	0.038
2452003.872330	17.151	0.037
2452003.874402	17.165	0.035
2452003.882411	17.162	0.035
2452004.045387	17.237	0.042
2452004.049391	17.257	0.046
2452004.053384	17.226	0.042
2452004.864304	17.383	0.039
2452004.866561	17.376	0.040
2452004.868818	17.359	0.036
2452004.872834	17.388	0.036
2452005.034086	17.316	0.038
2452005.038091	17.355	0.037
2452005.042095	17.364	0.043
2452005.863281	17.345	0.040
2452005.864751	17.303	0.040
2452005.866336	17.329	0.038
2452005.868315	17.308	0.040
2452005.870306	17.313	0.036
2452005.874311	17.332	0.037
2452005.878315	17.315	0.037
2452007.869857	17.427	0.039
2452007.871211	17.468	0.040
2452007.872357	17.442	0.037
2452007.876350	17.443	0.038
2452008.866519	17.613	0.039
2452008.870512	17.621	0.039
2452008.874517	17.605	0.039
2452011.862849	17.323	0.037
2452011.863856	17.333	0.037
2452011.865071	17.320	0.037
2452011.868046	17.322	0.037
2452011.869736	17.310	0.035
2452012.042792	17.313	0.036
2452012.046785	17.252	0.036
2452012.881861	17.427	0.040
2452012.885854	17.417	0.038
2452012.889859	17.419	0.038
2452013.027788	17.404	0.038
2452013.031781	17.372	0.038
2452013.035774	17.369	0.037
2452013.915965	17.155	0.035
2452013.924136	17.164	0.035
2452014.865566	17.291	0.038
2452014.869559	17.292	0.036
2452014.873552	17.291	0.037
2452015.897461	17.028	0.035
2452015.999127	17.052	0.035
2452016.003132	17.057	0.035
2452016.007125	17.061	0.036

TABLE 3
I photometry of April 2001 primary eclipse obtained with the 1.9 m telescope at MSO.

HJD	I (mags)	σ_I (mags)
2451998.899275	15.721	0.017
2451998.902181	15.694	0.022
2451998.904171	15.707	0.018
2451998.905977	15.718	0.022
2451998.909171	15.735	0.022
2451998.913697	15.720	0.024
2452000.903548	15.723	0.010
2452000.905469	15.720	0.011
2452000.907379	15.716	0.012
2452002.933307	15.735	0.011
2452002.935564	15.729	0.010
2452002.937833	15.727	0.011
2452003.923349	15.727	0.010
2452003.925617	15.726	0.010
2452003.927874	15.720	0.010
2452004.069056	15.765	0.015
2452004.071324	15.762	0.016
2452004.073593	15.769	0.016
2452004.917476	15.851	0.010
2452004.919732	15.855	0.010
2452004.922002	15.861	0.010
2452005.058588	15.850	0.015
2452005.060857	15.844	0.016
2452005.063125	15.849	0.015
2452005.918062	15.837	0.013
2452005.920330	15.849	0.014
2452005.922599	15.838	0.014
2452006.070412	15.863	0.010
2452006.072680	15.877	0.011
2452006.074948	15.851	0.012
2452007.896258	15.994	0.029
2452007.898515	15.979	0.023
2452007.900783	16.002	0.027
2452008.916242	16.017	0.012
2452008.918511	16.020	0.011
2452008.920780	16.016	0.011
2452011.918833	15.842	0.014
2452011.923358	15.854	0.013
2452012.059320	15.850	0.012
2452012.061589	15.858	0.011
2452012.921398	15.899	0.021
2452012.923678	15.900	0.018
2452012.925912	15.897	0.020
2452013.054211	15.864	0.010
2452013.058748	15.864	0.020
2452013.061167	15.859	0.014
2452013.871358	15.719	0.011
2452013.874413	15.719	0.011
2452013.876670	15.734	0.010
2452014.057147	15.739	0.011
2452014.059404	15.733	0.010
2452014.061672	15.736	0.011
2452014.915092	15.783	0.012
2452014.917349	15.789	0.013
2452015.915701	15.624	0.011
2452015.917970	15.622	0.011
2452015.920227	15.624	0.011

single-epoch all-sky survey in the JHK_s near-infrared bandpasses. These data (Table 4) were obtained from the 2MASS all-sky point source catalog, available online (Cutri et al. 2003).

3. MODEL AND RESULTS

The model and fitting procedure used here is that described in detail by Alcock et al. (2002) with only small modifications. Most notably the fit model has been adjusted to allow for eccentricity in the orbit of the stars. This is potentially a significant effect for this system as the orbit of an 800-day binary is unlikely to have been circularized. However, given the poorly defined (or possibly poorly covered) secondary eclipse in the current lightcurve its inclusion is unlikely to produce a significant improvement in the fit.

Figure 2 shows the four primary eclipses of 81.8997.87 for which we have observations along with the curve of best fit. The secondary eclipses are not shown because they cannot be clearly separated from the Cepheid variations with the current observational coverage (but they are included in the data published in Alcock et al. (2002)). The parameter set resulting from the fitting procedure is shown in Table 5. The ratio of the surface brightness in the V and R bands, J_V/J_R, a measurement of the color, is tabulated as it was the property that was fit directly and the other surface brightesses were computed from it. Each J_λ is expressed relative to the central surface brightness of the star. For the Cepheid we give the mean J_V/J_R to which a third order Fourier series, representing the intrinsic temperature change of the Cepheid, was added. For the Cepheid we also tabulate r_{min}, the star's minimum radius and ΔR_{amp}, the amplitude of the change in radius. Both are expressed in units of the orbital separation of the two stars as is the radius of the companion, r. The Cepheid's pulsation pe-

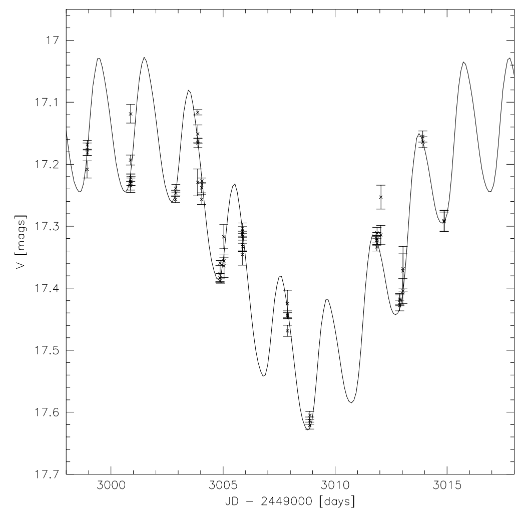

Fig. 1.— V-band observations of the April 2001 primary eclipse obtained on the 1.9 m telescope at Mount Stromlo Observatory along with the curve of best fit.

TABLE 4
2MASS JHK_s photometry of 81.8997.87 taken JD = 2451580.5850.

Filter	Magnitude	S/N
J	14.421 ± 0.039	42.1
H	13.989 ± 0.050	28.7
K_s	13.606 ± 0.049	23.9

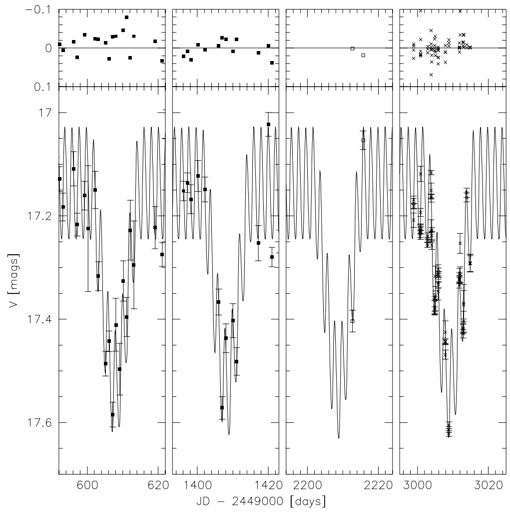

FIG. 2.— Primary eclipses of 81.8997.87 in V with the curve of best fit. The upper panels show residuals in magnitudes. Filled boxes indicate observations from the MACHO project, open boxes observations from the OGLE project and crosses observations taken on the 1.9 m telescope at Mount Stromlo Observatory.

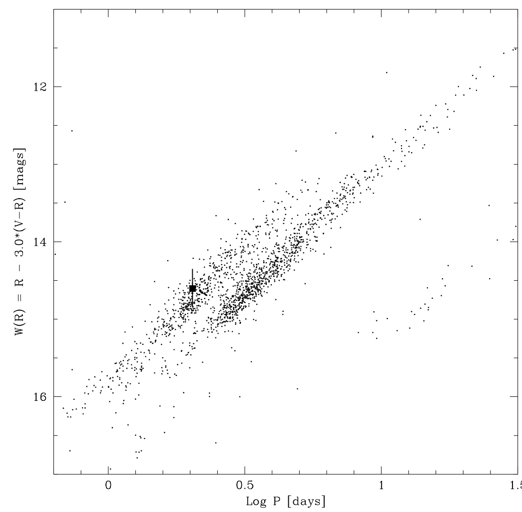

FIG. 3.— W_R vs. $\log P$ diagram for MACHO LMC Cepheids. The more luminous sequence at a given period contains Cepheids pulsating in the first overtone mode and the sequence extending to longer periods contains fundamental-mode pulsators. The sequence in the lower right contains the Type II (low-mass) Cepheids. The location of the variable component of this system (with the companion flux removed) is indicated by the large black square.

riod, P_{Ceph}, and ΔR_{shift}, the offset of the time of the Cepheid's minimum radius from the time zeropoint of the data, are both given in days. The uncertainties on these parameters are determined from the covariance matrix of the fitted parameters. From the surface brightnesses, radii and magnitude zeropoints, the intensity-weighted mean magnitude of each star in each filter is calculated. The mean colors are computed from the surface brightness ratios described above, not the individual magnitude values. Also tabulated for the Cepheid is the value of $W_R = R - 3.0(V - R)$ where $3.0 \sim A_R/(A_V - A_R)$ for this system (see below). This index will correct for most of the effects of reddening and differences in effective temperature between Cepheids. The uncertainty in the magnitude values are expressions of the range of possible magnitudes based on the uncertainties in the fit parameters. These are statistical uncertainties and likely underestimate the true uncertainties in these parameters. The orbital period is given in days and the inclination, i, is in degrees.

4. DISCUSSION

Figure 3 shows that the location of the Cepheid in the de-reddened Cepheid period-luminosity diagram is consistent with the overtone Cepheid population. This mode identification is confirmed by the shape of the lightcurve measured through Fourier-fitting (with the contamination due to the secondary removed). At a period of ~2 days the R_{21} Fourier parameter cleanly distinguishes between fundamental-mode and first-overtone Cepheids. The small amplitude of the change in radius (0.041 ± 0.001 of the minimum Cepheid radius) is also consistent with an overtone Cepheid. The magnitudes and colors in Table 5 are fainter and redder than expected for a Cepheid, which we interpret as significant extinction along the line of sight. MACHO field 81 contains regions of considerable star-formation activity.

By comparing the best-fit Cepheid magnitudes to those predicted by the V and I period-magnitude relations for overtone Cepheids of Baraffe & Alibert (2001), the amount of extinction in each bandpass and corrections for the magnitudes of each star can be estimated. These values are found to be: $A_V = 1.38$ mag and $A_I = 0.67$ mag. The relation

$$\left\langle \frac{A(I)}{A(V)} \right\rangle = 0.6800 - \frac{0.6239}{R_V} \qquad (1)$$

from Cardelli, Clayton, & Mathis (1989) yields $R_V = 3.15$ which, combined with the corresponding relation for the R band, gives $A_R = 1.04$. Applying these corrections we obtain the results shown in Figure 4. After correcting for extinction the companion's V magnitude and $V - R$ color seem consistent with a late-K or early-M class giant.

A possibility we considered is that the Cepheid is not an intermediate-mass object but is instead a Type II Cepheid. Mode identification based on Fourier parameters is not well established for Type II Cepheids of this period but based on the small photometric amplitude (0.21 mags in V) this Cepheid would still be classified as an overtone (Buchler & Buchler 1994). The theoretical $P - L$ relation of McNamara (1995) gives $M_V = -1.06$ mags for a Type II overtone Cepheid of this period, 1.78 magnitudes fainter than predicted for a Type I overtone. If zero extinction is assumed, $V = 17.2$ mags given in Table 5 implies a distance to the system of 44.8 kpc. This scenario is less likely because $V - R = 0.63$ mag for the Cepheid implies a temperature that is too cool to be consistent with the instability strip. A significant amount of extinction (see above) would need to be assumed with a concordant reduction in the assumed distance. This extinction could be Galactic or circumstellar.

The identification of the companion as a late-K or early-M class giant does not seem to be borne out by

TABLE 5
Best-fit Parameters for 81.8997.87 ($\chi^2_\nu = 1.5$)

Variable (Primary)		Companion (Secondary)	
Parameter	Value	Parameter	Value
$\left\langle \frac{J_V}{J_R} \right\rangle$	1.046±0.008	$\frac{J_V}{J_R}$	0.51±0.08
r_{min}	0.0365±0.0011	r	0.047±0.004
ΔR_{amp}	0.0014±0.0002	...	...
$P_{Ceph}(days)$	2.035375±0.000009	...	...
$\Delta R_{shift}(days)$	0.517±0.014	...	...
Intensity-weighted Mean Magnitudes and Colors			
$\langle V \rangle$	17.2±0.2	V	20.5±0.9
$\langle R \rangle$	16.5±0.2	R	19.0±0.9
$\langle I \rangle$	15.9±0.2	I	17.7±0.8
$\langle V-R \rangle$	0.63±0.01	$V-R$	1.4±0.3
$\langle V-I \rangle$	1.325±0.005	$V-I$	2.72±0.07
$\langle W_R \rangle$	14.4±0.2	...	...
Orbital Parameters			
$P_{orbital}(days)$	800.41±0.03		
$i(deg.)$	86.4±0.3		

Note. — Meanings of individual parameters and units are explained in the text.

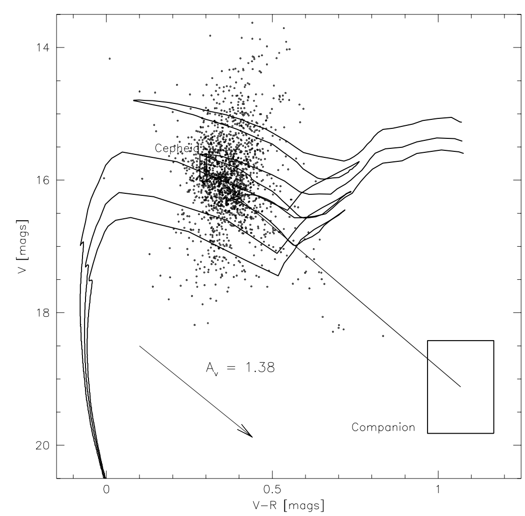

Fig. 4.— Color-magnitude diagram for MACHO LMC Cepheids. The boxes indicate the error bounds on the properties of the two components after the application of the extinction correction described in the text. The isochrones are from Lejeune & Schaerer (2001) and represent $\log_{10}(age)$ = 8.00, 8.14 and 8.25 (age in years). The arrow is the reddening vector for A_V = 1.38 mag as derived in the text.

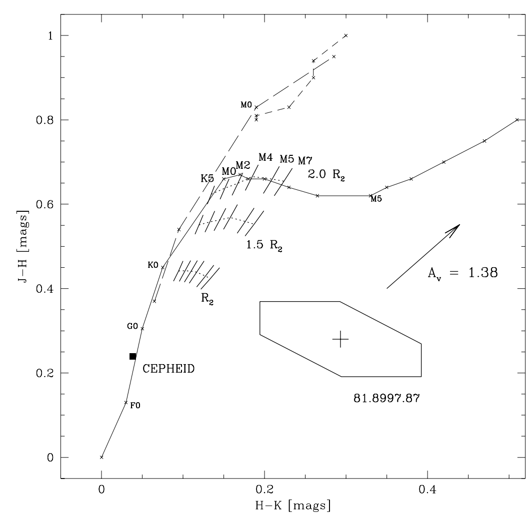

Fig. 5.— Near-IR color-color diagram with fiducial sequences for main sequence (solid black line) (Bessell 1991), giant (long-dashed black line) and supergiant stars (short-dashed black line)(Cox 2000). The 2MASS colors of the system 81.8997.87 are shown by the black cross and surrounding 1-σ error box, both have been corrected for extinction. The large filled square indicates the theoretical colors of a 2.035-day overtone Cepheid. The three sequences show possible combined colors of the two components assuming companion colors for giant stars from Bessell & Brett (1988). The sequence labeled R_2 assumes the two stars have radii in the ratio given by Table 5. The sequences labeled 1.5 R_2 and 2.0 R_2 show the effect of increasing the companion's radius by a factor of 1.5 and 2.0, respectively. The arrow is the reddening vector for A_V = 1.38 mag as derived in the text.

the infrared observations. The observed 2MASS colors for 81.8997.87 (corrected for extinction) along with the fiducial sequences for main sequence, giant and supergiant stars in the near-infrared color-color diagram are shown in Figure 5. Also shown are the theoretical location of a 2.035 day overtone Cepheid based on the relations of Groenewegen (2000) and sequences representing the combination of the theoretical Cepheid colors with a range of possible companion colors. The combined colors were computed assuming the ratio of radii given in Table 5 (for the sequence labeled R_2) and assigning the companion colors for late-type giants from Bessell & Brett (1988). The dotted line connects the different assumed spectral types while the solid lines reflect the range in possible colors arising from the uncertainty in the stellar radii. It is possible that the true radius of the compan-

ion is severely underestimated in the current fit to the (primarily) optical lightcurve. Thus two additional sequences, calculated by assuming that the companion's radius is 1.5 and 2.0 times larger than the value in Table 5, are also shown. The sequences for typical giant colors do not extend to cool enough temperatures to match the observed colors of this system. Only by assuming a much redder companion could we reproduce the observed colors of the system. This indicates that the system is unlikely to consist solely of an overtone Cepheid and another normal star.

It is possible that the 2MASS magnitudes are in error or that their uncertainties have been underestimated. All the statistics provided in the catalog indicate that these observations are reliable: high signal-to-noise ratio, good quality psf fit ($\chi^2_\nu = 1.29$, 0.92 and 0.97 for J, H and K respectively), source detected on all available frames. A more likely explanation would be the presence of a cool, contaminating object within the same resolving element as the target or the presence of hot circumstellar dust.

Figure 4 also shows that a system consisting of only these two stars is a poor fit to the expectations from standard, single-star evolutionary theory. It is possible that the system is not a binary but a hierarchical triple system (see discussion of V1334 Cyg by Evans (2000)). It is also possible that at some point in its history one of the components has undergone an episode of mass loss.

The possibility that this is a non-hierarchical triple system has been investigated by adding the presence of a third source of flux, not participating in the eclipses, to the model and testing whether this improves the fit to the observations. This would also rule out the possibility of an unrelated star along the line of sight. It was found that the quality of the fit improved slightly but, with a change in χ^2_ν of 0.015, not by a statistically significant margin. Thus, this result neither supports nor excludes the presence of additional sources of flux.

To attempt to further clarify the nature of this system we can estimate the properties of the variable star from the known properties of Cepheids and from its period and overtone classification. Bono, Gieren, Marconi, & Fouqué (2001) give the following canonical relation between period and radius for first overtone Cepheids:

$$\log R = 1.250(\pm 0.005) + 0.755(\pm 0.007) \log P, \qquad \sigma = 0.005 \tag{2}$$

where R has units of solar radii and P has units of days. This gives a predicted radius for our Cepheid of $30.4 \pm 0.4 R_\odot$. The ratio of stellar radii given by our fit then implies a companion radius of $39 \pm 4 R_\odot$. This radius is consistent with that of a giant star but is poorly constrained likely because of the absence of information from the system's secondary eclipses. Our best fit value of $r_1 = R_1/a$ gives an orbital separation of $a = 834 \pm 28 R_\odot = 3.9 \pm 0.1 AU$.

An estimate for the mass of the Cepheid can be obtained from the canonical Period-Mass-Radius relation for first overtone pulsators

$$\log M = -2.776(\pm 0.004) - 1.661(\pm 0.140) \log P + 2.682(\pm 0.185) \log R, \quad \sigma = 0.004 \tag{3}$$

with M in units of solar masses, P in units of days and R in units of solar radii, taken from Bono et al. (2001). With our period and radius values, this yields a Cepheid mass of $4.9 \pm 0.2 M_\odot$ which, for an 800.4 day orbital period and $a = 3.9 \pm 0.1 AU$, puts the companion's mass at $7.3 \pm 1.4 M_\odot$.

The binary system described above would have maximum radial velocities of $v_r \sin i = 31 \pm 4\ km\ s^{-1}$ for the primary and $v_r \sin i = 21 \pm 4\ km\ s^{-1}$ for the secondary. Therefore observations of the radial velocity curves would certainly be worthwhile provided a precision of $\pm 1\ km\ s^{-1}$ could be obtained.

5. CONCLUSIONS

We have presented additional optical observations and the first near-infrared photometry of this system. Combined with previously published optical data they support several conclusions:

1. Based on the updated set of optical magnitudes, colors and relative radii we can classify the components. They are most consistent with an intermediate-mass overtone Cepheid with a late K or M-type giant companion.

2. This result is inconsistent with the expectations from evolutionary theory. The companion is too cool and dim for the system to match theoretical isochrones.

3. In the near-infrared, a companion with cooler colors than standard giant stars is needed to replicate the observed system color.

Clearly, more observations are needed to fully realize the considerable potential of this system. In particular one of the principal sources of the uncertainty in the companion's properties is the lack of observations of a secondary eclipse. To facilitate follow-up work Table 6 presents a table of predicted future dates of primary and secondary eclipses.

Given the low temperature of the companion, observations taken at near-infrared wavelengths should put a stronger constraint on the companion's properties. In particular, precise photometry taken during the primary and secondary eclipses would allow better estimates of the individual colors of each component so their location in Figure 5 would be better determined. Observations taken on an 8m class telescope would have sufficient resolution to identify possible sources of contamination within the crowded field.

The companion and Cepheid would appear to have similar fluxes between J (1.22 μm) and H (1.63 μm) and therefore (given the estimated radial velocities given above) radial velocity work should be attempted with a high-resolution near-infrared spectrograph on an 8m-class telescope. Near-infrared spectra could also provide a more definitive classification of the companion star.

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TABLE 6
Predicted Dates of Future Eclipses

Primary Eclipse JD	Primary Eclipse UT	Secondary Eclipse JD	Secondary Eclipse UT
...	...	2,453,209.22	2004 Jul 22 5.34
2,453,609.84	2005 Aug 26 20.22	2,454,009.63	2006 Sep 30 15.18
2,454,410.25	2007 Nov 5 6.06	2,454,810.03	2008 Dec 9 0.78
2,455,210.66	2010 Jan 13 15.90	2,455,610.44	2011 Feb 17 10.62
2,456,011.06	2012 Mar 24 1.50	2,456,410.84	2013 Apr 27 20.22
2,456,811.47	2014 Jun 2 11.34	2,457,211.25	2015 Jul 7 6.06
2,457,611.87	2016 Aug 10 20.94	2,458,011.66	2017 Sep 14 15.90
2,458,412.28	2018 Oct 20 6.78	2,458,812.06	2019 Nov 24 1.50

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